Scientific approaches to science education

Understanding the way students and scientists think is the key to developing more effective methods of science teaching and is itself an intellectual challenge.

Frederick Reif

Our traditional approaches to science and mathematics education are based largely on intuitive notions and are, in some ways, rather unscientific. Whereas we usually tackle problems in science and engineering through the systematic use of fundamental principles, we often approach problems in science teaching by the seat of our pants, without deeper analysis. While we make great efforts in physics to understand the mechanisms that underlie observed phenomena, we are often content to consider scientists and students as "black boxes" whose internal intellectual functioning can be left largely unexamined in spite of its importance for teaching.

Common approaches to science teaching are often far less effective than we might hope. For example, numerous recent investigations reveal[1] that many students, after completing physics courses in which they seemingly performed well, exhibit gross misconceptions, revert to naive, prescientific notions when facing real situations and are often unable to apply their knowledge flexibly to solve simple problems.

By contrast, a more scientific approach to science education would strive to understand better the knowledge and thought processes that lead to good performance in the subject. It would seek to exploit the resulting insights in the design of effective instruction.

Such a systematic approach has three potential advantages:

▶ It should lead to a better fundamental understanding of human thought processes in complex domains. If pursued with sufficient seriousness, it should thereby also touch on basic issues recently addressed in cognitive psychology and artificial intelligence.

▶ It should lead to more principled and effective practical methods of science teaching.

▶ It should at least create a greater awareness of important issues and thereby reduce the likelihood that teachers adopt practices that are ineffective or even deleterious.

In this article I describe briefly some recent attempts to pursue such systematic approaches to science education, particularly in physics.

Frederick Reif is a professor of physics and a professor of education at the University of California, Berkeley. He is a member and former chairman of the Graduate Group in Science and Mathematics Education, an interdisciplinary group on the Berkeley campus.

Central issues

We can view learning or teaching as a transformation process in which the student S goes from an initial state S_i to a final state S_f of improved intellectual performance. To investigate this process systematically, we must answer four questions:

▶ What does the student know and how does the student think when in the initial state S_i, before instruction?

▶ What must the student know and how must the student think to achieve the desired intellectual performance—solving physics problems, for example—in the final state S_f?

▶ What learning or teaching process $S_i \rightarrow S_f$ takes the student from the initial state to the final state?

▶ What are the learning or teaching practices by which we can implement this transformation process?

These issues are analogous to those addressed in medicine. The central problem there is the transformation process that can take a person from an initial state of illness to a final state of good health. The following four issues must then be investigated and understood:

▶ the underlying mechanisms responsible for the disease

▶ the underlying mechanisms responsible for good physiological functioning

▶ the therapy that takes the patient from illness to health

▶ the medical practices and institutions for delivering the medical care.

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Physics instruction based on understanding of scientific thought processes. The student here is working with an instructional program on a computer with good graphics and artificial-intelligence capabilities. Such computers have been used for research on scientific thought processes, for designing instruction based on this research and for teaching. Figure 1

All these issues are complex and intellectually challenging in scientific medicine. The analogous issues are no less complex and challenging in a scientific approach to education.

Even a student's initial state S_i is unexpectedly complex because a student does not have a blank mind to be filled, but rather has a preexisting knowledge structure that must be modified. Indeed, recent investigations in physics[2] and other fields[3] show that students of all ages have acquired concepts and primitive theories about the world. From a modern scientific perspective, their conceptions may appear[4] to be misconceptions, and their primitive theories are often naive and fragmentary. Moreover, these theories are highly resistant to change and present major obstacles to new learning.

The realization that learning requires the restructuring of preexisting knowledge has important implications:

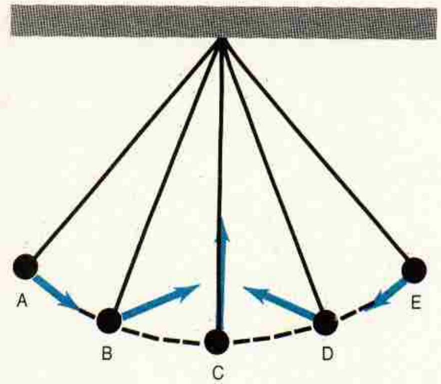
▶ Science curricula cannot merely specify what knowledge should be taught, but must also identify and deal explicitly with students' prior notions.

▶ The task of restructuring a student's preexisting knowledge is often more difficult than that of simply imparting new knowledge—and thus requires more sophisticated teaching methods (figure 1).

The most essential prerequisite for systematic instruction is an understanding of the knowledge and thought processes through which the student can achieve the desired performance. This performance goes beyond the recall of facts to involve the ability to solve problems and make scientific inferences. An analysis of such performance then requires answers to the following basic questions: What kinds of ancillary knowledge does the student need to interpret scientific concepts? How can the student organize scientific knowledge so as to appropriately retrieve it for problem solving? How can the student redescribe problems to facilitate their solution? What methods can the student use to make judicious decisions in the search for solutions?

Scientists themselves cannot answer such questions adequately because much of their knowledge is "tacit," that is, outside their conscious awareness. (Analogously, most native speakers cannot articulate the rules of grammar and sentence construction that underlie the language that they speak so well.) The tacitness of much expert knowledge becomes vividly apparent when one attempts—as researchers in artificial intelligence have[5]—to incorporate it in computer programs for solving problems with humanlike expertise.

Because much of their knowledge is tacit, instructors often fail to realize the full complexity of what students have to learn. Experts use some important knowledge so frequently that they take it for granted and do not teach it explicitly. Indeed, one can trace many



Acceleration of a swinging pendulum bob at various points. Many students say that the acceleration is zero at A or C, and that it is tangent to the path at B or D. The acceleration is actually nowhere zero and has the directions indicated by the arrows. Figure 2

student difficulties to a lack of knowledge or skills that were never explicitly taught. Even elucidating experts' tacit knowledge is insufficient for effective teaching, because students must often be taught explicit methods of performing tasks that experts do automatically because of years of experience.

In what follows, I illustrate the central issues by describing attempts to identify, and then to teach explicitly, some of the knowledge and thought processes required for solving scientific problems.

Interpreting scientific concepts

Many investigations have shown[1,2] that students have considerable difficulty interpreting scientific concepts. To study the issue more closely, we recently questioned[6] college students who for at least two months had been studying and using the concept of acceleration in an introductory mechanics course. Figure 2 illustrates the kind of questions we asked. For each position of the pendulum, we merely asked whether or not the acceleration was zero and, if not, to indicate its direction. More than half the answers were incorrect. We asked the students to talk about their thinking while working on the questions, allowing us to analyze their tape-recorded responses in detail. This study, as well as others, reveals that students' conceptual knowledge lacks coherence. For example, students usually interpret a scientific concept by retrieving miscellaneous associated knowledge fragments, many of which are incorrect; they rarely invoke a definition of a concept, usually cannot interpret it adequately even if they do; and they have no effective ways of resolving inconsistencies that they encounter.

The ancillary knowledge required to interpret[7] a scientific concept is actually quite complex. For example, to ensure that one can use a concept correctly, one needs both basic knowledge about the features that characterize the concept and knowledge of the *procedures* for identifying or constructing the concept. Such basic knowledge about acceleration, for example, includes a definition such as $\mathbf{a} = d\mathbf{v}/dt$ and a procedure such as indicated in figure 3. To ensure that one can interpret the concept rapidly and with little effort, one needs also a repertoire of knowledge about various special cases—acceleration in the case of circular motion, for example. The reliable and efficient interpretation of concepts, then, involves the joint use of both these kinds of knowledge, as well as the use of other knowledge not mentioned here.

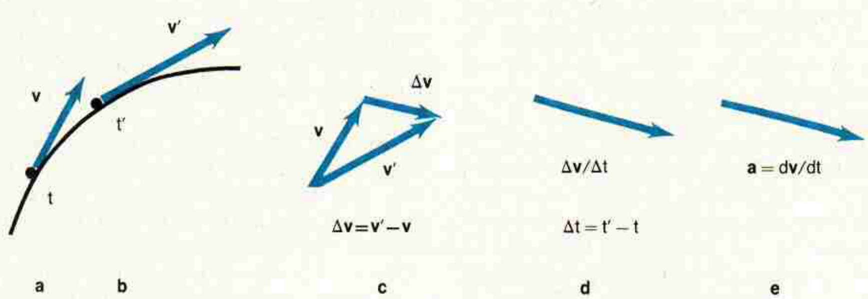
The behavior indicated by this model of good concept interpretation differs substantially from that of novice students, but does resemble that of scientists. Faced with the pendulum problem of figure 2, for example, the typical expert would determine the acceleration at C by invoking *special knowledge* about circular motion with constant speed, but would find the acceleration at A by the *general procedure* of comparing velocities. Nevertheless, even some physics professors have difficulties answering the seemingly simple questions of figure 2.

To explore some instructional implications of this model of good concept interpretation, we taught students explicitly the procedure specifying the concept of acceleration; we gave them practice in independently implementing this procedure, and we had them use the procedure to detect, diagnose and correct their own mistakes and "mistakes" purported to have been made by someone else. After this instruction, which lasted about half an hour, students were able[6] to answer correctly 29 out of 30 questions about acceleration, no longer invoked the misconceptions that they had used earlier, diagnosed most of their earlier difficulties and were able to detect and correct mistakes committed by someone else.

This study had some limitations, particularly its failure to investigate long-term learning. Nevertheless, it indicates the virtue of teaching explicitly the procedural and diagnostic knowledge needed for the reliable interpretation of concepts. Such explicit teaching is rare in common practice, where concepts are often introduced by mere definitions or vague analogies.

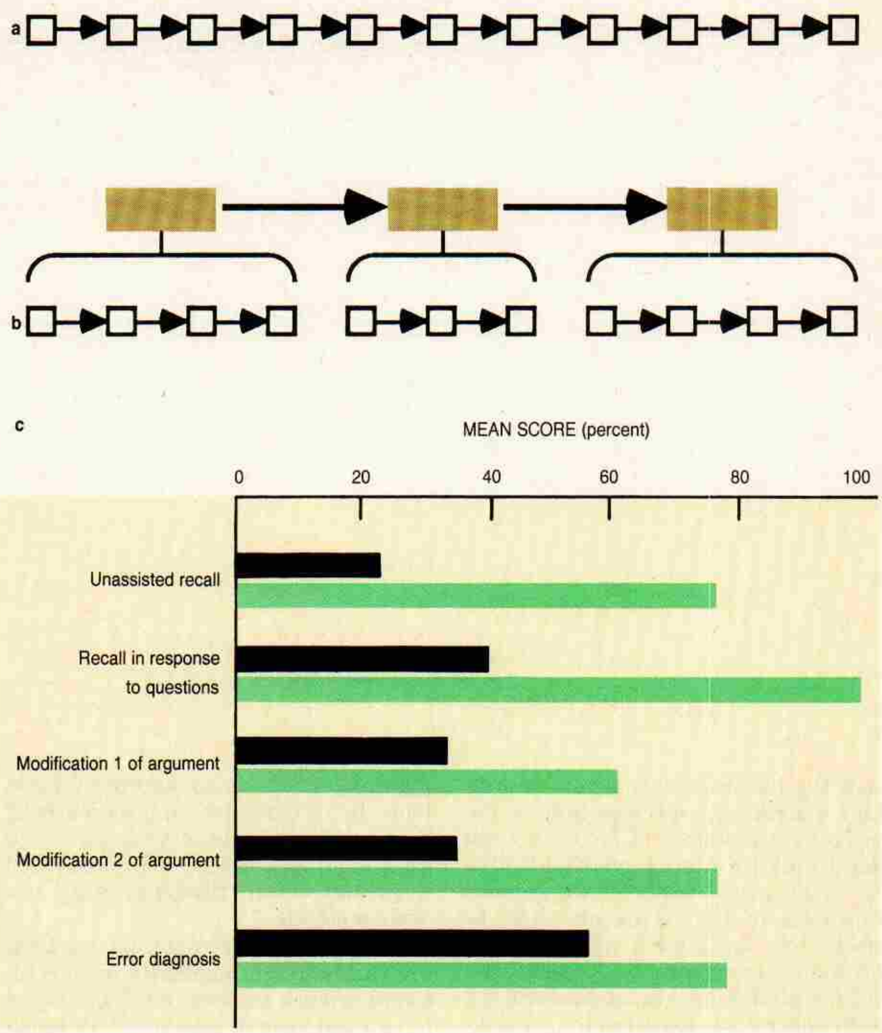
Organization of knowledge

Our ability to use knowledge effectively depends crucially on the manner in which it is organized. The individual



Procedure defining the acceleration of a particle. **a:** Identifying the velocity **v** of the particle at the time *t* of interest. **b:** Identifying its velocity **v**′ at a slightly later time *t*′. **c:** Finding the change of velocity Δ**v**. **d:** Finding the ratio Δ**v**/Δ*t*. **e:** Finding the limiting value of this ratio when *t*′ → *t*. Figure 3

Knowledge organization and its effect on the performance of various tasks. **a:** Schematic representation of the linear organization of a scientific argument. **b:** Hierarchical organization of the same argument. **c:** Performance of students using linearly organized knowledge (black bars) and hierarchically organized knowledge (colored bars). Figure 4



folders in a file cabinet, for example, may be full of valuable information, but this information is nearly useless if the folders are arranged randomly. Hence there arises the fundamental question, how should a person organize knowledge so as to facilitate remembering, retrieving, problem solving and learning?

To examine how organizing the same scientific information differently might affect intellectual performance, we did an experiment[8] in which two groups of students were made to remember the same scientific argument—the solution to a problem—but in different ways. One group remembered the argument organized in a "linear" form: as a sequence of detailed steps leading from the premises to the conclusion. The other group remembered the argument organized in a "hierarchical" form: as a sequence of a few major steps, each of which was elaborated into several detailed steps. As figure 4 shows, the students with the hierarchical organization were much better able to recall the argument, to trace the effects of errors in the argument and to modify the argument when the premises were changed. Such results are to be expected because the hierarchical structure makes it easier to retrieve information and to "see the forest amidst the trees."

The advantages of organizing knowledge hierarchically become even more apparent in more complex domains. For example, large computer programs are structured[9] hierarchically to make them easier to design, comprehend and modify. Entire fields of scientific knowledge, such as mechanics, can also be advantageously organized[10] in hierarchical form.

Such cognitive investigations suggest that we should pay at least as much attention to the organization of the knowledge acquired by students as we do to the content of that knowledge—something we rarely do. Scientific arguments and prototypical problem solutions, for example, are commonly presented in a purely linear, rather than hierarchical, form. Although this practice is logically impeccable, it does not leave students in the best position to use the information that they have been given, nor does it present them with good models of how to organize knowledge effectively.

Problem solving

Because problem solving is crucial for making scientific inferences, the solutions of various problems are commonly presented and discussed in science courses. However, the solution to a problem may reveal little about the underlying thought processes that generated it. Although a solution shows a particular reasoning path that leads to a desired goal, it does not indicate how this particular path was found, how it was chosen over alternative paths or how impasses were avoided. These are precisely the thinking skills that students must learn if they are to generate independently the solutions of unfamiliar problems. Yet such thinking processes are rarely taught explicitly. It is scarcely surprising that many students find problem solving difficult and often remain poor problem solvers.

The thought processes required for problem solving include:

▶ generating a description of the problem that makes it easier to solve

▶ making judicious decisions in searching for the solution

▶ testing and revising the solution.

Recent research in cognitive science has elucidated[11] some of these processes and has led to teaching applications in physics,[12] mathematics[13] and biology.[14] Here I shall briefly mention some examples pertinent to physics.

The way a problem is described can be crucial in determining the difficulty of finding its solution. Experts often redescribe problems almost unconsciously, while students often have substantial difficulty doing so. In one of our studies[15] we gave students mechanics problems similar to those they had recently encountered in a basic physics course that they had completed with a grade of B or better. About half of the students' solutions were wrong because they incorrectly described motion or forces (see figure 5).

Our analysis suggests that it should be possible to formulate explicit procedures for redescribing problems effectively in any given area. We formulated a procedure applicable to all problems in elementary mechanics. This procedure, which is much more explicit

than the limited advice given in ordinary instruction, specifies how to describe both motion and forces, how to identify all the interactions that lead to the forces, how to explicate the general properties of the forces and how to check that the motion and force descriptions are consistent. To test[15] the efficacy of this general procedure, we used controlled experimental conditions to ensure that students used the procedure to describe several problems, such as the one in figure 6. As shown in figure 5, students generated correct descriptions of all these problems, and correct solutions for almost all of them.

These results suggest that we should teach explicit general procedures for describing problems. Adequate explicitness is a crucial ingredient. As figure 5 shows, when students in our experiment used a less explicit description procedure, their problem-solving performance deteriorated appreciably.

The central difficulty of problem solving is the need to make judicious decisions to find, among the many reasoning paths that lead nowhere, one that leads to the desired goal. Although there are no prescriptions guaranteeing good decisions, there are systematic methods[10,11] that can make the search for a solution much easier, especially compared to the haphazard methods used by many students. In particular it is helpful to diagnose at every stage the difficulties of a problem—for example, the absence of needed kinds of equations of the presence of unwanted quantities. One can then address subproblems aimed at reducing these difficulties. Furthermore, experts commonly use powerful planning methods to approach problems by progressive approximations: Schematic solutions serve as guides to final solutions, which are elaborated in greater detail. Students rarely use such methods.

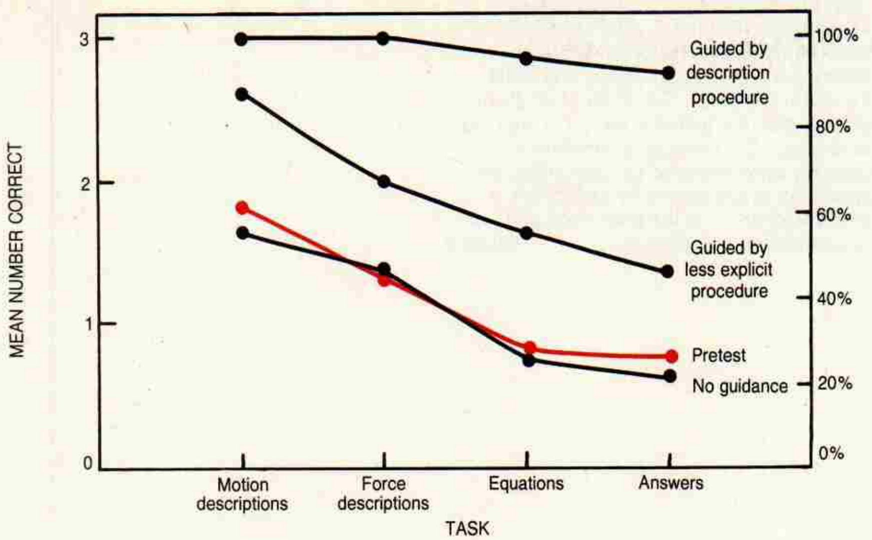
Such decision or planning methods are rarely taught explicitly in conventional science courses, although there have been recent attempts[13] to teach some of them in special contexts. Some teaching practices, prevalent in mathematics and the physical sciences, may even be deleterious because of their excessive emphasis on mathematical symbolism and quantitative problem formulations. They thereby encourage students' tendencies to invoke miscellaneous formulas, and discourage students from using the kinds of qualitative reasoning useful for planning solutions or solving problems by progressive refinement.

Principled instruction

Understanding the thought processes required for good intellectual performance in a particular discipline should lead to the design of effective practical methods for teaching such thought processes. Recent educational efforts pursuing such a systematic approach show considerable promise. Some such efforts, well summarized[16] in a recent review article, have focused on teaching reading with good comprehension, teaching writing for effective communication and teaching mathematical problem solving.

The work on reading comprehension, for example, identified and explicitly taught[17] skills for clarifying, summarizing and predicting that readers can use to extract meaningful knowledge from prose. The instruction featured a novel method called "reciprocal teaching," in which the instructor and the student take turns teaching each other. This method, which one could readily apply to science instruction, is powerful because it engages students very actively, forces them to be explicit about their thinking and behavior, teaches them both to create and to criticize, provides them with immediate feedback and allows them to become progressively more independent as the instructor provides less and less help. As a result of such systematic instruction, students' average reading-comprehension test scores increased from 15% to 85% after 20 training sessions and remained at 60% six months later. Even in some classroom studies involving less individualized instruction, scores were raised from 40% to 75%. These are impressive results for any teaching effort.

Computers can play a very useful role in the study of instructional principles and in their practical application. Research on instruction can be made more rigorous and explicit by translating instructional models into forms in which they can be incorporated into computer programs. The computer also allows better control of conditions in instructional experiments. Computers can allow[18] students to explore new ideas actively and thereby to develop insight and intuition. Computers can also act[19] as effective private tutors, particularly if the programming is based on good cognitive analyses and exploits the techniques of artificial intelligence. Such computer tutors



Performance on physics problems by students guided by an explicit description procedure (top curve), by students guided by a less explicit procedure (middle curve) and by students using their own methods of description. The points indicate the mean numbers of problem solutions (out of three) featuring correct descriptions of the motion, correct descriptions of the forces, correct equations and correct answers. Figure 5

have recently been designed and used[20] to teach geometry and the computer language LISP.

Prospects and difficulties

All the efforts I have described in this article strive to base instruction upon an understanding of thought processes. They attempt to address educational problems with a greater emphasis on theoretical analyses and experimental investigations, to extend to education systematic approaches common in other scientific fields, and to transcend thereby ideas derived solely from intuitive notions and practical experience.[21] Historically, many fields—physics, metallurgy, agriculture and medicine, for example—started as arts, crafts or philosophical speculations and gradually became transformed into theoretically based sciences with extensive practical applications. There is reason to believe that education might similarly become more of an applied science, perhaps comparable to modern medicine even if not as successful as applied physics.

The prospects seem particularly opportune at present. Recent advances in cognitive sciences such as information-processing psychology, artificial intelligence and linguistics have led[22] to significant new insights into the way people think. Furthermore, dramatic advances in information technologies—especially computers—have made available powerful new tools for research and education. These scientific and technological developments provide potent means for addressing educational problems in a more analytic fashion.

There has been progress: Important educational issues have been identified; deleterious teaching practices have been uncovered; complex cognitive processes have become better understood; promising new teaching methods have been explored. These results are encouraging, but it would be foolish to claim that they are more than beginnings. However, it would be equally foolish, especially for scientists, to minimize the long-term potential of principled analytic approaches.

Some significant difficulties hamper development of the potential of analytic approaches to education. The greatest of these is probably a shortage of talent. The advancement of any field, be it physics, molecular biology, medicine or any other science, depends crucially on the existence of critical-size groups of people of first-rate talent. The problem is particularly severe in education because pursuit of promising new directions requires expertise in several areas—mathematics and natural science, cognitive science, computers and artificial intelligence, educational fields and some social sciences. Persons with such unusual combinations of qualifications are very rare. Furthermore, only at a very few places, such as the University of California at Berkeley, the University of Pittsburgh and Carnegie–Mellon University, are there the beginnings of interdisciplinary groups possessing jointly the necessary kinds of expertise. This talent problem has prompted several recent recommendations[23] to establish national centers, much like the NSF-sponsored centers in engineering and theoretical physics, designed to foster significant educational advances by assembling the requisite interdisciplinary expertise and physical resources. However, it remains to be seen whether such recommendations will be implemented.

The shortage of talent can ultimately be traced to a lack of students being prepared to work along newer lines in education. The situation is only gradually beginning to change. A few universities, such as Berkeley, now have special PhD programs stressing the application of cognitive science and computation to science education. The job opportunities for students graduating from such programs appear increasingly good. Some students who are well trained in mathematics, physics or artificial intelligence are beginning to be attracted to modern education. The best such students are those who deviate from more traditional scientific careers because they perceive that education is a field ripe for progress, with substantial intellectual challenges, new scientific and technological bases and major social implications. However, we shall need many more such students to realize the new opportunities for substantial advances in education.

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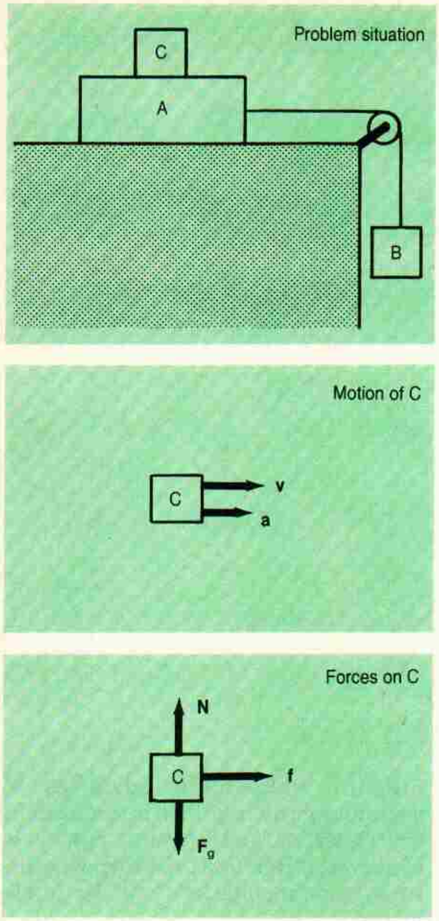

Test problem of the type used in the experiments of figure 5. The questions concern block C. The lower diagrams describe the motion of the block and the forces on the block. Students often claim wrongly that the frictional force **f** is directed to the left. The description procedure prevents such mistakes by explicating the properties of forces and by having the students check that the total force and acceleration are consistent. Figure 6

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